APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

METHOD AND APPARATUS FOR LWD SHEAR VELOCITY MEASUREMENT

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CROSS REFERENCES TO RELATED APPLICATIONS

[0001] This application claims priority from United States Provisional Patent Application Ser. No. 60/248,097 filed on November 13, 2000. This application is also related to United States Patent Application Ser. No. 09/590,906 filed on June 9, 2000, having the same assignee as the present application and the contents of which are fully incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This invention generally relates to a method and apparatus for measuring and processing a characteristic of subsurface earth formations penetrated by a borehole. More specifically this invention relates to a method and apparatus for measuring and processing an acoustic characteristic such as formation shear wave velocity of subsurface sonic waves after these waves traverse earth formations adjoining a borehole or passing through a portion of the subsurface.

BACKGROUND OF THE INVENTION

[0003] To obtain hydrocarbons such as oil and gas, wellbores (also referred to as the boreholes) are drilled by rotating a drill bit attached at the end of a drilling assembly generally referred to as the "bottom hole assembly" (BHA) or the "drilling assembly." The wellbore path of such wells is carefully planned prior to drilling such wellbores utilizing seismic maps of the earth's subsurface and well data from previously drilled

wellbores in the associated oil fields. Due to the very high cost of drilling such wellbores and the need to minimize time actually spent drilling and wireline logging wells, it is essential to gain as much information as possible during drilling of the wellbores. Information about downhole conditions and materials may be acquired with wireline

5   tools or bottom hole assemblies (BHA). Wireline tools are generally used after a wellbore is drilled, bottom hole assemblies may be used while the well is being drilled as part of the drilling string. Downhole wellbore information acquired from BHA components may be utilized, among other things, to monitor and adjust the drilling direction of the wellbores or to detect the presence of geologic formations and

10   hydrocarbons.

[0004] In logging while drilling through an earth formation, it is desirable to measure formation shear wave velocity. The shear wave velocity of earth formations provides information important for exploration and production of oil and gas from the formation.

15   The shear wave velocity profile enables the conversion of seismic shear wave time sections to depth sections and is utilized in the interpretation of seismic wave amplitude variation versus detector offset. The ratio between the shear wave velocity and the compressional wave velocity is closely related to the rock lithology and is related to hydrocarbon saturation. Shear wave velocity is also used to evaluate the mechanical

20   properties of the formation in reservoir engineering applications.

[0005] Because of the importance of earth formation shear velocity, various methods have been developed to measure it. In conventional wireline logging using a monopole

acoustic tool, the shear velocity can be measured from the shear wave refracted along the

borehole wall if the formation shear wave velocity is greater than the borehole fluid

acoustic velocity. A formation that has a shear wave velocity faster than the borehole

fluid is called a 'fast formation.' However, in a formation where the shear velocity is

5   slower than borehole fluid velocity, a 'slow formation,' the shear wave can no longer

refract along the borehole wall, and the shear velocity cannot be directly measured from

monopole logging. Because of the need to measure shear velocity in slow formations,

especially in the soft sediments of deep-water reservoirs, dipole acoustic logging tools

were developed. The dipole tool induces and measures the bending or flexural wave

10   motion in the formation. In a sufficiently low frequency range (1-3 kHz), the flexural

wave travels at the shear velocity of the formation, regardless whether the formation is

fast or slow. This allows for direct measurement of formation shear velocity using the

dipole acoustic tool. Dipole acoustic logging is now a mature technology with

worldwide commercial applications.

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[0006] A viable technique for shear wave velocity measurement is using the quadrupole

shear waves. A quadrupole acoustic tool induces and measures the quadrupole shear

wave in the formation. The low-frequency portion of the wave travels at the formation

shear wave velocity, allowing for direct shear velocity measurement from the quadrupole

20   wave. Although the quadrupole shear wave has been extensively studied theoretically

and a wireline quadrupole-logging tool was also proposed (Winbow et al., 1991 in US

Patent No. 5,027,331), this technology has not yet been commercially applied to the oil

and gas industry. This is largely because the wide acceptance and success of the dipole

shear wave technology have fulfilled the needs for measuring shear velocity in slow formations.

[0007] The acoustic Logging-While-Drilling (LWD) technology has been developed in recent years out of the needs for saving rig-time and for real-time applications such as geosteering and pore pressure determination, among others. The LWD acoustic technology is aimed at measuring the compressional- and shear-wave velocities of an earth formation during drilling. This technology has been successful in the measurement of compressional wave velocity of earth formations. The need for determining the shear wave velocity in slow formations calls for further development of the technology for shear wave measurement capability. Because of the popularity and success of the dipole shear wave technology in wireline logging, this technology is naturally extended to the LWD situation and a LWD dipole acoustic tool has been built and offered for commercial applications.

[0008] As discussed later in the application, the application of the dipole acoustic technology to LWD has a serious drawback caused by the presence of the drilling collar with BHA that occupies a large part of the borehole. The drawback is that the formation dipole shear wave traveling along the borehole is severely contaminated by the dipole wave traveling in the collar. There is a need for a method of determination of shear wave velocities of earth formations that is relatively robust in the presence of tool mode waves propagating along the drill collar. The need is particularly acute in situations where the formation shear velocity is less than the velocity of propagation of compressional waves

in borehole fluids. The present invention satisfies this need and, additionally, also provides a method for determination of shear velocities in "fast" formations where the shear velocity exceeds the compressional velocity of borehole fluids.

SUMMARY OF THE INVENTION

[0009] The present invention is an apparatus and method of determining formation shear properties in a Logging while Drilling environment. In a preferred embodiment of the invention, a transmitter is operated at a frequency below a cut off frequency of a signal propagating through the drill collar so that the signal received at receiver is uncontaminated by the collar mode. The cutoff frequency is determined by the thickness of the drill collar. In a preferred embodiment of the invention, the transmitter is a quadrupole transmitter. The quadrupole mode in a collar has a cutoff frequency that is higher than the quadrupole mode in the formation, so that operating a quadrupole transmitter below this cutoff frequency gives a signal relatively uncontaminated by the tool mode. In a fast formation where the formation shear velocity exceeds the compressional velocity of the borehole fluid, higher order quadrupole modes may be analyzed to determine the formation shear velocity.

[0010] In an alternate embodiment of the invention, the transmitter is operated without regard to the cutoff frequency and the received signals are low-pass filtered to reject the tool mode.

[0011] In a preferred embodiment, the transmitter comprises eight azimuthally

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segmented elements. The receiver may be a quadrupole receiver or a dipole receiver.

When a dipole receiver is used, the quadrupole transmitter is operated twice with

different polarizations and the two received signals are then processed to give a received

quadrupole signal

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[0012] The receivers are preferably located between the transmitter and the drillbit.

Noise generated by the drillbit is received at the receivers with a direction of propagation

opposite that of signals produced by the transmitter. The receivers may be operated as a

phased array to reject the noise generated by the drillbit.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The novel features which are believed to be characteristic of the invention, both as

to organization and methods of operation, together with the objects and advantages

15   thereof, will be better understood from the following detailed description and the

drawings wherein the invention is illustrated by way of example for the purpose of

illustration and description only and are not intended as a definition of the limits of the

invention:

FIG. 1A shows a schematic diagram of a drilling system that employs the apparatus of

20   the current invention in a logging-while-drilling (LWD) embodiment.

FIG. 1B illustrates a LWD tool on a drill collar.

FIG. 2 illustrates velocity dispersion curves for formation and drill-collar dipole modes.

FIG. 3 illustrates dipole acoustic waveforms in the presence of a drilling collar.

FIG. 4A shows is a schematic illustration of the field for a quadrupole wave.

FIG. 4B illustrates velocity dispersion curves for formation and drill-collar quadrupole modes.

FIG. 5A illustrates wavefield snapshots of acoustic energy near the borehole, where radial particle velocity associated with the quadrupole wave motion is displayed.

FIG. 5B illustrates quadrupole waveforms at various offsets.

FIG. 6A illustrates wavefield snapshots of acoustic energy near the borehole, where radial particle velocity associated with the quadrupole wave motion in a thin-collared pipe is displayed.

FIG. 6B shows time domain displays of the data in Figure 6A.

FIG. 7 illustrates a simplified perspective view of a source cross-section in conjunction with the drilling collar.

FIG. 8 illustrates a detailed cross-sectional view of a segmented ring transmitting implementation of a source.

FIG. 9 illustrates a detailed cross-sectional view of a compartmentalized segmented transmitting implementation of a source.

FIG. 10 is a perspective view of the sensor layout around the collar.

FIG. 11 illustrates a detailed cross-sectional view of a segmented ring receiving sensor implementation.

FIG. 12 illustrates a detailed cross-sectional view of a compartmentalized segmented receiving sensor implementation.

FIGURES 13A and 13B show the preset invention using two receiver elements for detection of quadrupole signals.

FIG. 14 illustrates a side view of a portion of the device of Figure 12.

FIG. 15 shows the higher order quadrupole modes in a fast formation.

FIG. 16 shows the equivalence of a quadrupole to a pair of dipoles.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

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[0014] The present invention is a method, system and apparatus for measuring shear wave formation velocities while a well is being drilled. To the extent that the following description is specific to a particular embodiment or a particular use of the invention, this is intended to be illustrative and is not to be construed as limiting the scope of the

10 invention.

[0015] **Figure 1A** shows a schematic diagram of a drilling system **10** having a bottom hole assembly (BHA) or drilling assembly **90** that includes sensors for downhole wellbore condition and location measurements. The BHA **90** is conveyed in a borehole

15 **26.** The drilling system **10** includes a conventional derrick **11** erected on a floor **12** which supports a rotary table **14** that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drill string **20** includes a tubing (drill pipe or coiled-tubing) **22** extending downward from the surface into the borehole **26.** A drill bit **50**, attached to the drill string **20** end, disintegrates the geological

20 formations when it is rotated to drill the borehole **26.** The drill string **20** is coupled to a drawworks **30** via a kelly joint **21**, swivel **28** and line **29** through a pulley (not shown). Drawworks **30** is operated to control the weight on bit ("WOB"), which is an important parameter that affects the rate of penetration ("ROP"). A tubing injector **14a** and a reel

(not shown) are used instead of the rotary table **14** to inject the BHA into the wellbore when a coiled-tubing is used as the conveying member **22**. The operations of the drawworks **30** and the tubing injector **14a** are known in the art and are thus not described in detail herein.

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[0016] During drilling, a suitable drilling fluid **31** from a mud pit (source) **32** is circulated under pressure through the drill string **20** by a mud pump **34**. The drilling fluid passes from the mud pump **34** into the drill string **20** via a desurger **36** and the fluid line **38**. The drilling fluid **31** discharges at the borehole bottom **51** through openings in

10   the drill bit **50**. The drilling fluid **31** circulates uphole through the annular space **27** between the drill string **20** and the borehole **26** and returns to the mud pit **32** via a return line **35** and drill-cutting screen **85** that removes the drill cuttings **86** from the returning drilling fluid **31b**. A sensor S_1 in line **38** provides information about the fluid flow rate. A surface torque sensor S_2 and a sensor S_3 associated with the drill string **20** respectively

15   provide information about the torque and the rotational speed of the drill string **20**. Tubing injection speed is determined from the sensor S_5, while the sensor S_6 provides the hook load of the drill string **20**.

[0017] In some applications only rotating the drill pipe **22** rotates the drill bit **50**.

20   However, in many other applications, a downhole motor **55** (mud motor) is disposed in the drilling assembly **90** to rotate the drill bit **50** and the drill pipe **22** is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction. In either case, the ROP for a given BHA largely depends on the WOB or the

thrust force on the drill bit **50** and its rotational speed.

[0018] The mud motor **55** is coupled to the drill bit **50** via a drive disposed in a bearing assembly **57**. The mud motor **55** rotates the drill bit **50** when the drilling fluid **31** passes through the mud motor **55** under pressure. The bearing assembly **57** supports the radial

5 and axial forces of the drill bit **50**, the downthrust of the mud motor **55** and the reactive upward loading from the applied weight on bit. A lower stabilizer **58a** coupled to the bearing assembly **57** acts as a centralizer for the lowermost portion of the drill string **20**.

[0019] A surface control unit or processor **40** receives signals from the downhole sensors

10 and devices via a sensor **43** placed in the fluid line **38** and signals from sensors S_1-S_6 and other sensors used in the system **10** and processes such signals according to programmed instructions provided to the surface control unit **40**. The surface control unit **40** displays desired drilling parameters and other information on a display/monitor **42** that is utilized by an operator to control the drilling operations. The surface control unit **40** contains a

15 computer, memory for storing data, recorder for recording data and other peripherals. The surface control unit **40** also includes a simulation model and processes data according to programmed instructions. The control unit **40** is preferably adapted to activate alarms **44** when certain unsafe or undesirable operating conditions occur.

20 [0020] The BHA may also contain formation evaluation sensors or devices for determining resistivity, density and porosity of the formations surrounding the BHA. A gamma ray device for measuring the gamma ray intensity and other nuclear and non-nuclear devices used as measurement-while-drilling devices are suitably included in the

BHA **90.** As an example, **Figure 1A** shows an example resistivity-measuring device **64**

in BHA **90.** It provides signals from which resistivity of the formation near or in front of

the drill bit **50** is determined. The resistivity device **64** has transmitting antennae **66a** and

66b spaced from the receiving antennae **68a** and **68b.** In operation, the transmitted

5   electromagnetic waves are perturbed as they propagate through the formation

surrounding the resistivity device **64.** The receiving antennae **68a** and **68b** detect the

perturbed waves. Formation resistivity is derived from the phase and amplitude of the

detected signals. The detected signals are processed by a downhole computer 70 to

determine the resistivity and dielectric values.

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[0021] An inclinometer **74** and a gamma ray device **76** are suitably placed along the

resistivity-measuring device **64** for respectively determining the inclination of the portion

of the drill string near the drill bit **50** and the formation gamma ray intensity. Any

suitable inclinometer and gamma ray device, however, may be utilized for the purposes

15   of this invention. In addition, position sensors, such as accelerometers, magnetometers

or gyroscopic devices may be disposed in the BHA to determine the drill string azimuth,

true coordinates and direction in the wellbore **26.** Such devices are known in the art and

are not described in detail herein.

20   [0022] In the above-described configuration, the mud motor **55** transfers power to the

drill bit **50** via one or more hollow shafts that run through the resistivity-measuring

device **64.** The hollow shaft enables the drilling fluid to pass from the mud motor **55** to

the drill bit **50.** In an alternate embodiment of the drill string **20,** the mud motor **55** may

be coupled below resistivity measuring device **64** or at any other suitable place. The above described resistivity device, gamma ray device and the inclinometer are preferably placed in a common housing that may be coupled to the motor. The devices for measuring formation porosity, permeability and density (collectively designated by numeral **78**) are preferably placed above the mud motor **55**. Such devices are known in the art and are thus not described in any detail.

[0023] As noted earlier, a significant portion of the current drilling systems, especially for drilling highly deviated and horizontal wellbores, utilize coiled-tubing for conveying the drilling assembly downhole. In such application a thruster **71** is deployed in the drill string **90** to provide the required force on the drill bit. For the purpose of this invention, the term weight on bit is used to denote the force on the bit applied to the drill bit during the drilling operation, whether applied by adjusting the weight of the drill string or by thrusters. Also, when coiled-tubing is utilized a rotary table does not rotate the tubing; instead it is injected into the wellbore by a suitable injector **14a** while the downhole motor **55** rotates the drill bit 50.

[0024] **Figure 1B** is a schematic view of an acoustic logging while drilling tool system on a BHA drill collar **90** containing a drill bit **50**. This system is mounted on the BHA drill collar **90** for performing acoustic measurements while the formation is being drilled. The acoustic logging while drilling tool system has a source **105** to emit acoustic vibrations **106** that may traverse formation **95** and may also be propagated along the borehole wall and be received by sensors A and B which may be in arrays. These sensors

are discussed later in the application. A point to note is that the sensors are disposed between the transmitter and the receiver. This has important benefits in that the desired signal produced by the transmitter travels in a direction opposite to the direction of noise generated by the drillbit **50**. This makes it possible to use suitable filtering techniques, including phased arrays, to greatly reduce the drillbit noise. In an alternated embodiment of the invention, the transmitter **105** may be located between the sensors and the drillbit **50**

[0025] The application of the dipole acoustic technology to LWD has a serious drawback caused by the presence of the drilling collar with BHA that occupies a large part of the borehole. The drawback is that the formation dipole shear wave traveling along the borehole is severely contaminated by the dipole wave traveling in the collar. This is demonstrated by the following theoretical analysis/numerical modeling results.

[0026] The dipole wave excitation and propagation characteristics for a borehole with a drilling collar are analyzed. Using known analyses methods, for example the analyses of the type described in Schmitt (1988), one can calculate the velocity dispersion curve for the formation and collar dipole shear (flexural) waves. The dispersion curve describes the velocity variation of a wave mode with frequency. In the example, the borehole diameter is 23.84 cm and the inner- and outer diameter of the collar is 5.4 and 18 cm. respectively. The inner collar column and the annulus column between the collar and borehole are filled with drilling mud whose acoustic velocity and density are 1,470 m/s and 1 g/cc, respectively. The collar is made of steel (compressional velocity, shear

velocity and density of steel are 5,860 m/s, 3,130 m/s, and 7.85 g/cc, respectively). The formation is acoustically slow with compressional velocity of 2,300 m/s, shear velocity 1,000m/s, and density 2 g/cc. It is to be noted that the example is for illustrative purposes only and not intended to be a limitation on the scope of the invention.

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[0027] The calculated drilling collar and formation flexural wave dispersion curves for dipole modes are shown in **Figure 2,** for the frequency range shown as the horizontal axis of 0 to 14 kHz. The collar dipole wave dispersion curve **201** displayed along the vertical axis shows how velocity of the collar dipole wave varies with frequency over the

10 range 0 to 14 kHz. The formation dipole wave dispersion curve **203** shows that except for low frequencies in this range, there is relatively little change in velocity. The formation and collar flexural wave modes coexist almost for the entire frequency range, except at the very low frequency where the collar flexural mode appears to terminate at the formation shear velocity. Below the frequency where the collar mode terminates, the

15 formation flexural mode velocity appears to continue the collar flexural mode behavior that would exist in the absence of the formation, the velocity decreasing to zero at the zero frequency. This cross-over phenomenon is caused by the strong acoustic interaction between the collar and the formation in this dipole excitation situation.

20 [0028] Dipole acoustic wave propagation in a borehole with a drilling collar may be simulated with numerical finite difference techniques, for example as described in Cheng et al. (1995). The model parameters are the same as used in the above velocity dispersion calculation example. The dipole source and an array of receivers are placed on

the rim of the collar. The source excitation center frequency is 2 kHz. **Figure 3** shows

the simulated dipole acoustic waveforms displayed with time along the horizontal axis.

Dipole acoustic waveforms are displayed by offset corresponding to source-receiver

distance along the vertical axis in **Figure 3**. Receiver locations are spaced 0.1524m apart

5   beginning with the near trace waveform at 1.833m 301 to 2.9m 303 offset from the

source. The dipole acoustic waveforms are dominated by the collar flexural wave that

has a faster velocity and a dispersive character. The initial strong impulses **305** of the

dispersive collar flexural wave are followed in time by dispersive energy that is stronger

than the flexural wave of interest representing the formation S-wave. The dashed line

10   **335** represents the arrival location and velocity of the formation flexural wave. The

formation flexural wave of interest, aligned with dashed line **335**, is smaller in amplitude

compared with the collar flexural wave, and is severely contaminated by the interaction

of the collar flexural wave.

15   [0029] The above velocity dispersion calculation and wave propagation simulation

results demonstrate that there is a strong interaction between formation and drilling collar

flexural waves. The fundamental cause of this is that the two wave modes coexist in the

same frequency range of interest. There are several drawbacks of the LWD dipole

technology for shear velocity measurement. The first is the difficulty in obtaining good

20   quality formation flexural wave measurements in the presence of severe contamination

from the collar flexural wave. The collar wave, being a low-frequency mode, is difficult

to suppress using attenuation techniques such as cutting grooves and/or inserting

absorptive materials in the collar, etc. The second drawback is that the formation

flexural wave, even if it could be reliably measured, cannot yield accurate formation shear velocity information because of the collar interaction. As can be seen from **Figure 2,** the high frequency limit of the collar mode approaches the shear velocity of the collar and at the frequency **205** where the collar dipole mode ceases to exist, the velocity of the collar dipole mode is the formation shear velocity **207**. The velocity **203** of the formation dipole mode is, at all frequencies, below the formation shear velocity **205**. In the absence of a collar, when excited at low frequencies, the formation dipole mode would propagate at a velocity equal to the formation shear velocity. Determination of the formation shear velocity from the dispersion curves of either the formation dipole mode or the collar dipole mode not an easy matter. In addition, during drilling operations, there is a strong dipole mode excited by the drillbit that produces additional noise. For the foregoing reasons, it is difficult, if not impossible, to measure formation shear wave velocity using the dipole acoustic technology in the LWD environment.

[0030] The preferred manner of deploying certain sensors for LWD shear wave data acquisition, for example in drill string BHA **90** of **Figure 1A** and **1B** will now be described. The actual BHA utilized for a particular application may contain some or all of the sensors described in the background section, in addition to the present invention. For the purpose of this invention any such BHA could contain one or more seismic sources and receivers (collectively represented herein by numeral **88**) at a suitable location in the BHA **90.**

[0031] This invention incorporates a quadrupole acoustic technology for the LWD shear

velocity measurement. **Figure 4a** shows an illustration of a quadrupole field. It shows a characteristic four-lobed pattern that may be substantially characterized by a $cos\ 2\theta$ azimuthal variation. In the present instance, the field may be associated with particle motion or with pressure. The greatest advantage of using the quadrupole wave is that the

5   collar quadrupole wave exists only above a certain frequency called the cut-off frequency. This frequency depends on the drilling collar thickness and borehole size. Thus, by determining the cut-off frequency for the collar and borehole dimensions, one can select a frequency band in which only the formation quadrupole shear wave is excited. Determining the velocity of the formation quadrupole wave will fulfill the

10   needs for shear wave velocity measurement in the LWD environment. This is different from the situation in wireline logging: while *Winbow* does discuss the use of quadrupole logging on a wireline device, there is no discussion of a cutoff frequency of a quadrupole wave. *Winbow* teaches a wireline logging device. As would be known to those versed in the art, the tool diameter in wireline devices is typically much smaller than the borehole

15   diameter. *Chen* has also discussed the use of a quadrupole source for shear wave logging and shows a comparison of experimental results with theoretical dispersion curves for Stoneley waves within the borehole. The tool diameter *Chen's* model is less than half the borehole diameter. As would be known to those versed in the art, Stoneley waves are interface waves propagating along the wall of the borehole. In contrast, the present

20   invention deals with a MWD device wherein the diameter of the drill collar is almost the same as the diameter of the borehole. In such a case, the collar mode becomes important. This collar mode is different from the Stoneley waves discussed in *Chen*.

[0031] The feasibility of determining formation shear velocity from quadrupole wave measurement is demonstrated using theoretical/numerical analysis examples. **Figure 4-b** shows the velocity dispersion curves of the formation 401 and collar quadrupole waves **403** and **405**. Velocity in meter per second (m/s) is displayed along the vertical axis and frequency in kilohertz (kHz) along the horizontal axis. The velocity dispersion curve for an exemplary collar of thickness 35mm is shown as curve **403.** The velocity dispersion curve for an exemplary collar of thickness 63mm is shown as curve **405.** The formation quadrupole wave is slightly dispersive and reaches the formation shear wave velocity at a low cut-off frequency (around 2 kHz in this case). This indicates that formation shear wave velocity can be determined as the low frequency limit of the velocity of formation quadrupole waves. The collar quadrupole wave velocity curve shows very high values due to the high shear rigidity (steel) and thick wall (63 mm) of the drilling collar. The collar wave for the 63mm thick collar **405**, however, exists only in the frequency range above 10 kHz; whereas, the required frequency for shear velocity measurement of the formation is around 2 kHz, well separated from the frequency range (> 10 kHz) of the collar wave. This frequency separation allows for designing a method and apparatus to generate quadrupole waves only in a predetermined frequency band (0-10 kHz in this case). In this band, only the formation quadrupole wave is generated. This wave excitation/generation scheme may be demonstrated using finite difference simulations.

[0032] In a finite difference modeling, a quadrupole source and an array of receivers with a 0.1524 m. spacing are placed at the rim of the collar. The source wavelet center frequency is chosen to be 2 kHz, the amplitude spectrum of the source wavelet

diminishing to zero at about 5 kHz, which is below 10 kHz, the cut-off frequency of the collar quadrupole wave. **Figure 5a** shows three snapshots in time of the wavefield intensity due to the quadrupole source. Each snapshot, **501**, **503**, and **505** is a cross-section displaying a fluid inside the drill collar **521**, the drill collar **90**, fluid **523** outside the drill collar, and a formation **95**. Radial particle velocity associated with the quadrupole wave motion is displayed shaded **507**, **509**. These **Figure 5a** snapshots display the locations of wavefield intensity at several instants of time (0.24 milliseconds for 501, 1.22 milliseconds for **503**, and 2.21 milliseconds for **505**, respectively). In the borehole fluid annulus high wavefield intensity is seen **507** and high wavefield intensity is seen in the formation **509**. The wave motion in the fluid annulus and the motion in the formation are in phase, traveling at the formation shear velocity as demonstrated by the juxtaposition of high wavefield intensity in the fluid **507** and the formation **509** for all three snapshots **501**, **503** and **505**. This is the formation quadrupole wave as discussed in connection with **Figure 4**. There is almost no discernable wave intensity for locations anywhere inside the collar except for the initial time (snapshot 0.24 ms **501**) around the source, showing that the collar quadrupole wave is not excited in this frequency band for this collar thickness (2.48 inches).

[0033] The time-domain quadrupole waveforms of the receiver array are displayed in **Figure 5B** where time is represented along the horizontal axis. Quadrupole acoustic waveforms are displayed by offset corresponding to source-receiver distance along the vertical axis in **Figure 5B**. Receiver locations are spaced 0.1524m apart beginning with the near trace waveform at 1.833m **531** to 2.9m **533** offset from the source. **Figure 5B**

shows only one wave, the formation quadrupole wave, traveling across the array at the formation shear velocity. The dashed line 535 marks the formation quadrupole wave first arrival. This time-domain wave simulation result is consistent with the frequency domain dispersion analysis result of **Figure 4**. These examples demonstrate that

5   choosing an appropriate wave excitation frequency band can eliminate collar quadrupole waves.

[0034] The excitation frequency band should be selected based on the drilling collar and borehole dimensions. In drilling practice, the size of the borehole is varied to suit

10   exploration/production needs and/or geological environment of the well to be drilled. Accordingly, the size of the drilling collar also varies. The change of the collar and borehole dimensions, especially the former, will significantly change the collar quadrupole wave characteristics. This, again, can be demonstrated using theoretical/numerical analysis examples. The quadrupole dispersion curves for a 35 mm

15   thickness drilling collar (dashed curves) are shown in **Figure 4**. With the thinner collar, the formation quadrupole dispersion curve (dashed line **403**) is also changed. The cut-off frequency of the formation mode is raised to about 3 kHz and the whole curve exhibits higher values compared to the thick collar case (solid curve **405**). The curve approaches the formation shear wave velocity at low frequencies. On the other hand, the collar

20   quadrupole wave velocity is much reduced compared to the thick collar case (solid curve 405) and shows a much lower cut-off frequency (about 6 kHz). The general trend shown in Figure 4 is that increasing the collar thickness will move the frequency band of the collar quadrupole wave away from that of the formation quadrupole wave. When the

frequency band of the collar quadrupole wave is close to that of the formation

quadrupole, measurement of the formation quadrupole wave will be severely impaired, as

the following wave simulation example demonstrates.

5   **[0035]** The example case is where the collar pipe is relatively thin (thickness is only 16

mm or 0.63 inches). The cut-off frequency of the collar quadrupole wave is now about

3.5 kHz. Other parameters, as used in the simulation of **Figure 5B**, are kept unchanged.

With the 2 kHz center excitation frequency, both formation and collar quadrupole waves

are excited. **Figure 6A** is the counterpart of **Figure 5A**, showing the wavefield snapshots

10   for the 16mm thick collar case. **Figure 6A** shows three snapshots in time of the

wavefield intensity due to the quadrupole source. Each snapshot, **601**, **603**, and **605** is a

cross-section displaying a fluid **621** inside the drill collar, drill collar **90**, fluid **625**

outside the drill collar, and a formation **95.** Radial particle velocity associated with the

quadrupole wave motion is displayed shaded **611**, **613.** These **Figure 6A** snapshots

15   display the locations of wavefield intensity at several instants of time (0.24 milliseconds

for **601**, 1.22 milliseconds for **603**, and 2.21 milliseconds for **605**, respectively). In the

borehole fluid **625** annulus high wavefield intensity is seen **611** and high wavefield

intensity is seen in the collar **613.** For all the three time instants **601**, **603** and **605**, the

wavefield intensity in the entire borehole containing the collar is dominated by the collar

20   quadrupole wave. Formation quadrupole wave is weakly excited, which is out of phase

with the collar wave.

[0036] The time domain array waveforms are shown in **Figure 6B**. The time-domain

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quadrupole waveforms of the receiver array are displayed in **Figure 6B** where time is

represented along the horizontal axis. Quadrupole acoustic waveforms are displayed by

offset corresponding to source-receiver distance along the vertical axis in **Figure 6B**.

Receiver locations are spaced 0.1524m apart beginning with the near trace waveform at

5   1.833m **631** to 2.9m **633** offset from the source. The time domain waveforms are

dominated by the collar quadrupole wave that has a moveout velocity of about 1,300 m/s.

The dashed line **635** represents the arrival time for the formation quadrupole wave. In

this case, it is difficult to measure the formation quadrupole wave in the presence of the

strong collar wave. This example demonstrates the importance of the frequency band

10   selection for the LWD quadrupole wave generation and measurement devices.

[0037] The above examples demonstrate the advantage of the quadrupole shear wave in

the LWD environment and the requirements that facilitate making the LWD quadrupole

shear wave measurement. As a result, a quadrupole LWD shear wave system can be

15   constructed. Quadrupole shear waves in the LWD environment can be generated using a

quadrupole source mounted on the drilling collar **90**. **Figure 7** is a simplified perspective

view of the source cross-section in conjunction with the drilling collar. As shown in

Figure 7, the quadrupole source comprises the drilling collar **90** and eight members of

equal dimension. The sections are number **701-708**. These members are eight equal

20   sectors of the source cylinder. The cylinder sections are made from either an

electrostrictive (or piezoelectric) or a magnetostrictive material capable of generating

stress/pressure wave signals from the input electric pulse. In an alternate embodiment of

the invention (not shown) the sections comprise electromechanical devices of such

devices are shown in US Patent 5,852,262 to *Gill*, the contents of which are incorporated

herein by reference. Included in the teachings of *Gill* is an actuator that produces a

pressure pulse. By use of suitably configured portholes, dipole or quadrupole pulses may

be produced. Bender bars may also be used. Although dividing the source cylinder into

5   four equal sectors suffices to produce a quadrupole source, using eight (or any multiple

of four) sectors for the source reduces the mass of each sector so they more easily

withstand drilling vibrations. While the description of the source herein uses eight

source segments as an example, those versed in the art would recognize how any multiple

of four sources could be excited to produce a quadrupole signal.

10

[0038] The lower part of **Figure 7** is a cross-sectional view of the quadrupole shear wave

source on the plane perpendicular to the axis of the drilling collar. The elements of the

source device are, in one embodiment, eight sectors labeled **701, 702, 703, 704, 705, 706,**

707 and **708.** When electrical pulses are applied to the source, each sector will expand or

15   contract in a radially outward or inward manner. Specifically, the electrical pulses can be

applied such that sectors (**701, 702**) and diametrically opposed sectors (**705, 706**) will

expand and simultaneously, sectors (**703, 704**) and sectors (**707, 708**) will contract, as

illustrated in **Figure 7.** Then four stress/pressure waves will be generated in the

surrounding borehole fluid/formation, as well as in the drilling collar. It is also to be

20   noted that when a device such as that taught in *Gill* is used, there may only be a single

actuator that produces quadrupole signals from suitable portholes.

[0039] When all eight sectors are made from the same material and the electrical pulses

applied to them have substantially the same amplitude, then the interaction of the four

pressure/stress waves inside the drilling collar and in the surrounding borehole/formation

will produce quadrupole shear waves. More specifically, if the electrical pulses are

modulated such that the frequency band of the generated pressure/stress waves is below

5   the cut-off frequency of the quadrupole shear wave in the drilling collar, then the

interaction of the four stress waves in the collar will cancel each other. The interaction of

the pressure/stress wave in the borehole and formation will produce a formation

quadrupole shear wave to propagate longitudinally along the borehole. This frequency

band modulation of the source pulses is part of one embodiment of the present invention.

10

[0040] An actual implementation of the quadrupole shear wave source is now described

in more detail. **Figure 8** illustrates a detailed cross-sectional view of a segmented ring

transmitter implementation. This implementation has a segmented ring mounted on an

elastomeric isolation component **801** in a continuous pocket **803** around the collar **90.**

15   The isolation component is used to reduce drill string induced acoustic signals. The

sensor sub assembly can be oil-filled with a cover sleeve **807**, as illustrated, or it can be a

potted assembly, requiring no oil. An electronic drive circuit(s) **809** is coupled to the

transmitter element(s) **811** to excite acoustic signal(s) into the borehole and formation. A

cover sleeve **815** may cover transmitter elements **811.** The electronic drive circuit **809**

20   may be placed in the inner mandrel **813.** The transmitting element(s) **811** can be

implemented in various forms to include rings, cylinders, plates, and piston or solenoid

elements. The number of segments can be increased in circumferential and/or axial

direction as needed.

[0041] Figure 9 illustrates a detailed cross-sectional view of a compartmentalized segmented transmitting implementation which has segments mounted on individual elastomeric isolation components **901** in compartmentalized pockets **903** around the collar **90**. There may be oil fill **907** between the transmitting element **911** and a cover sleeve **915**. The transmitting electronics **909** may reside in the inner mandrel **813**.

[0042] The quadrupole shear wave in the earth formation produced by the above described quadrupole source may be detected at locations spaced longitudinally along the borehole from the source, as schematically illustrated in **Figure 1B**. **Figure 1B** is a schematic view of an acoustic logging while drilling tool system on a BHA drill collar **90** containing a drill bit **50**. This system is mounted on the BHA drill collar **90** for performing acoustic measurements while the formation is being drilled. The acoustic logging while drilling tool system may have a source **105** to emit acoustic vibrations **106** that may traverse formation **95** and be received by sensors A and B which may be in arrays. The use of arrays with axially spaced apart elements as shown in **Figure 1B** makes it possible to use well-known phased array filtering techniques for attenuating signals traveling in a particular direction with a specified range of velocities. In a preferred embodiment of the invention, this phased array filtering is used to attenuate noise generated by the borehole. The phased array filtering may also be used to attenuate the collar mode by defining a range of velocities to be attenuated. In an alternate embodiment of the invention, a plurality of axially spaced apart transmitter elements is used and the phased array filtering is used to reduce the generation of collar mode signals.

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[0043] As shown in **Figure 10** for an embodiment of the present invention, acoustic detectors may be mounted at the rim of the drilling collar. Each detector consists of four similar sensors circumferentially spaced around the collar, for example sequentially named as A, B, C, and D. **Figure 10** is a perspective view of a sensor layout around the

5   collar in relation to source elements as described in **Figure 7**. The center of each sensor is longitudinally aligned with a junction of two source sectors that expand/contract simultaneously. For example, sensor A is aligned with the junction between source sectors **701** and **702**, sensor B is aligned with the junction between source sectors **703** and **704**, etc. The four-sensor detector acts to enhance the efficiency of the quadrupole

10   source and to remove possible contamination from a monopole component of the wave signal.

[0044] An actual implementation of the quadrupole shear wave receivers as quadrupole detector arrays is now described in more detail. **Figure 11** illustrates a detailed cross-

15   sectional view of a segmented ring receiving sensor implementation which has a segmented ring mounted on an elastomeric isolation component **1101** in a continuous pocket **1103** around the collar **90**. The isolation is used to reduce drill string induced signals. The sensor sub assembly can be oil-filled **1107** with a cover sleeve **1115**, as illustrated or it can be a potted assembly, requiring no oil. An electronic signal

20   conditioning circuit(s) **1109** is coupled to the receiver element(s) **1111** to sense acoustic signal(s) in the borehole and formation. The receiver circuit **1109** may reside within the inner mandrel **813**. The receiving element(s) can be implemented in various forms to include rings, cylinders, plates, and piston or solenoid elements. The number of

segments can be increased in a circumferential and/or axial direction as needed. The

material for the receiver elements may be selected from a piezoelectric material, an

electrostrictive material; and, a magnetostrictive material.

5   [0045] Figure 12 illustrates a detailed cross-sectional view of a compartmentalized

segmented receiving sensor implementation which has receiver segments 1211 mounted

on individual elastomeric isolation components 1201 in compartmentalized pockets 1203

around the collar 90. The inner mandrel 813 holds receiver circuit 1209, which is

coupled with a receiver element 1211. The receiver element 1211 has a cover sleeve

10   1215 with an oil filled space 1207 in between.

[0046] Copending United States Patent Application Ser. No. 09/590,906, the contents of

which are fully incorporated herein by reference, teaches how a quadrupole mode may

obtained by suitable combination of signals received by two receiver elements with two

15   different excitations of a quadrupole transmitter.

[0047] This is illustrated in Figure 13a showing another embodiment of the invention in

which a quadrupole excitation is provided by four segments 1401a - 1401d of a

transmitter. Alternatively, the quadrupole signal could be provided by pairing adjacent

20   segments of the eight-element transmitter discussed above. Hereafter, when references

are made to four element transmitters and receivers, it is to be understood that these are

intended to cover eight element transmitters and receivers as well. The signal, after

propagating through the formation, is detected by a dipole receiver 1410 comprising

receiver elements **1403a** and **1403c**. Subsequently, a quadrupole mode is excited as in

Figure 13b by the transmitter **1400** and received by the same receiver elements **1403a**

and **1403c**. Denoting by A and C the signals received by the receiver elements **1403a**

and **1403b** for the transmitter firing of **Figure 13a**, and by A^* and C^* the signals received

5   by the receiver elements **1403a** and **1403b** in **Figure 13b**, by performing the operation

$$S = (A + C) - (A^* + C^*),$$

the signal S will be a quadrupole signal with all common modes including the

BHA/drillbit signals attenuated. These common modes include the body wave through

10   the tool, monopole signals (P and S) through the formation and Stoneley waves within

the borehole. The Stoneley waves are more of a problem with an MWD tool than with a

wireline tool due to the smaller annulus between the tool and the borehole wall:

consequently, removal of the common modes is more important than for wireline

logging.

15

[0048] **Figure 14** shows a side view of a receiving sensor segment. The collar **90**

contains a transducer element **1211** that includes a plurality of active elements **1251**. The

other components in **Fig. 14** are as in **Figure 12** and are not discussed further.

20   [0049] The signals received from, for example, the **Figure 10** sensors A, B, C, and D

may be combined as (A+C)-(B+D). For the source configuration and firing scheme

shown in **Figure 7**, the generated quadrupole wave arriving at the sensors A, B, C, and D

can be described as follows. Sensors A and C will see, respectively, a pressure wave of

the same polarity and amplitude, and sensors B and D, a pressure wave of the same amplitude but reversed polarity. Therefore, adding the signals from A and C and subtracting the signals from B and D, as (A+C)-(B+D), will produce a signal four times stronger than each individual signal of one sensor. Moreover, a LWD quadrupole source, when placed off the borehole axis, as is often the case during drilling, will also generate a monopole component to propagate along the borehole. At low frequencies, the monopole wave will propagate as a tube wave to contaminate the formation quadrupole shear wave. The low frequency tube wave motion is substantially homogeneous inside the borehole, such that each individual sensor will measure substantially the same tube wave signal. This monopole tube wave can be canceled out by the combination (A+C)-(B+D).

[0050] An alternative embodiment of the invention is the low-pass filtering of the signals recorded by each sensor below the cut-off frequency of the collar quadrupole wave. If the source pulses have high frequencies and are not modulated, or if the quadrupole component of the drilling noise has frequency content above the cut-off frequency of the collar quadrupole wave, then the collar quadrupole wave will be excited and recorded by the sensors. Because the collar quadrupole wave exists only above its cut-off frequency, it can be removed by low-pass filtering the sensor signals below the cut-off frequency. As stated above, this cut-off frequency can be determined from the borehole and drilling collar dimensions. Thus the low-pass filter can be designed and installed as a part of the sensor data acquisition and processing system.

[0051] For signal coherence enhancement and processing purposes, arrays of the above-

mentioned detectors/receivers are placed longitudinally along the drilling collar. The

spacing between the adjacent detectors typically ranges from 0.5 to 1 ft (0.1524 to 0.3048

m). The formation shear wave velocity may be determined by correlating the quadrupole

shear wave across the receiver array using any standard array processing method as

5   taught in United States Patent 5,441,890 to *Tang*.

[0052] The above discussion has been directed towards determination of formation shear

velocities by what would be recognized by those versed in the art as the first order mode.

In "fast" formations where the shear velocity exceeds the compressional velocity in the

10   borehole fluid, higher modes may exist. This is illustrated in **Figure 15a.** The abscissa

is the frequency and the ordinate is the velocity. **1301a** and **1301b** show an example of

the phase and group velocities of the 1st order quadrupole mode while **1303a** and **1303b**

show the phase and group velocities of the 2nd order mode. The formation shear- and

compressional-wave velocities are 4,500 and 2,500 m/s, respectively; the drilling collar

15   and borehole dimensions and other related parameters are the same as in Figure 5B. The

waveform simulation uses a 5-kHz center-frequency source. Two quadrupole modes

exist in the frequency range below 21 kHz. They are named the first and the second

quadrupole mode, respectively, with the higher order mode existing in a higher frequency

range. For the example in **Figure 15A,** the first and the second mode starts to appear

20   from about 3 and 8 kHz, respectively. The first mode shows a steeply decreasing phase

dispersion curve **1301a** with a well-defined group velocity **1301b** minimum. The

presence of the group velocity minimum produces a phenomenon called the Airy phase.

The associated waveforms are shown in **Figure 15B**. The wave energy associated with

the Airy phase dominates the waveforms and lags significantly behind the formation

shear-arrival time **1311**, as shown in **Figure 15B**. In this situation, it is difficult, if not

impossible, to measure the fast formation shear-wave velocity from the waveform data

for the first mode.

5

[0053] Measuring the waveform of the second quadrupole wave mode can directly

determine the fast formation shear velocity. As shown in **Figure 15A**, in a broad

frequency range above the cut-off frequency, the phase velocity curve of the second

mode is very close to the formation shear velocity (2,500 m/s in this case). Both the

10   phase and group velocity curves of the second mode are quite flat, indicating minimal

dispersion effects. In fact, the quadrupole wave excited in this higher frequency range,

which is associated with the second mode, propagates at the formation shear-wave

velocity, as illustrated in **Figure 15B**. Since the second quadrupole mode of the

formation can be effectively excited below the frequency range of the collar quadrupole,

15   the interference from the latter mode can still be avoided or minimized. As shown in

Figure 15B, there is no discernable wave energy associated with the collar quadrupole.

The example shown in **Figures 15A, 15B** shows that one can reliably determine the

formation shear-wave velocity by exciting and measuring the second quadrupole wave

mode associated with a fast formation.

20

[0054] The above examples have used a unitary drill collar to illustrate the principles of

using quadrupole mode excitation for determination of formation shear properties in a

LWD environment. For practical reasons, the logging tool of the present invention may

comprise multiple segments of drill collars with transmitters and receivers on different

segments of the drill collar. The principles described above are equally applicable to

such segmented drill collars and are intended to be within the scope of the invention. It

is possible that the cut-off frequency and the dispersion curves may be different for each

5   segment of the drill collar. This does not affect the principles of operation of the logging

tool.

[0055] The above examples have further illustrated the implementation of quadrupoles

by at least two pairs of matched "monopole" elements wherein elements within each pair

10   move in unison. An alternative method for excitation of a quadrupole signal or reception

of a quadrupole signal is possible using two dipoles, such as bender bars. This is

illustrated in **Figure 16** . The elements **1401 – 1403** comprise one dipole, e.g., a first

bender bar, and the elements **1405-1407** comprise a second dipole, e.g., a second bendor

bar. The motion of the bender bars is not radial: it is orthogonal to a radial line joining

15   the center of the tool to the midpoint of the bender bar; nevertheless, a significant

quadrupole signal may be excited or received by the configuration shown in **Figure 16**.

Such an implementation is intended to be within the scope of the present application.

[0055] The above description has been made with respect to a LWD application of the

20   invention. The present invention may also be used in Logging-while-Tripping. As

would be known to those versed in the art, it is common for drillbits to wear out and the

process of removing a drillstring for the purpose of changing a drill bit is called

"tripping." Making measurements while tripping has the additional advantage that no

drilling is being carried out, so that the signals received by the receivers of the present logging tool are not contaminated by drillbit generated noise.

[0056] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

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